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Optical parametric chirped-pulse amplification (OPCPA) has the potential to produce extremes of peak and average power, but is either limited in *energy* by crystal growth issues, or limited in *average power* by the nonlinear OPA crystal thermo-optic characteristics. Large (7.5 cm diameter x 25 cm length) crystals of yttrium calcium oxyborate (YCOB) have been recently grown and utilized for high average power second harmonic generation. YCOB crystals possess the capability to scale to large apertures and have the necessary thermo-optic properties required for scaling to high peak and average power operation for 1 μm as well as 2 μm OPCPA systems. We have demonstrated optical parametric chirped-pulse amplification utilizing YCOB for the first time. The scalability to high peak and average power in this new nonlinear crystal is addressed.

OCIS codes: (190.4970) Optical parametric amplifiers and optical parametric oscillators; (320.7090) Ultrafast lasers; (190.4400) Nonlinear optics, materials

Optical parametric chirped-pulse amplification[1] (OPCPA) is an enabling technology that allows the direct scaling of short pulse laser technology to new extremes of peak[2] as well as average power, with the capability of operating at user selectable wavelengths and attaining compressed pulse widths, in some instances, shorter than those offered by fixed-frequency laser-gain media. However, just as the wavelength and minimum pulse duration of chirped-pulse amplification (CPA) sources are fixed by the gain characteristics of the laser host medium, scaling to high peak and high average power is limited in OPCPA by the nonlinear optical crystal characteristics. Peak power is limited by the available aperture, pulse duration is controlled by the product of nonlinear gain and intrinsic dispersion, and average power limits are derived from the thermo-optic properties (optical absorption, thermal conductivity, thermal dephasing) of the available crystals. Three nonlinear optical crystals have been utilized in high-energy single shot and moderate average power OPCPA applications: KH_2PO_4 or KD_2PO_4 (KDP or DKDP)[2], LiB_3O_5 (LBO)[3], and BaB_2O_4 (BBO)[4]. LBO and BBO are limited to 2 cm apertures due to intrinsic growth issues, resulting in a maximum available amplified signal energy of less than 3 J. While KDP crystal growth has been demonstrated in apertures exceeding 40 cm, a small nonlinear coefficient and poor thermo-optic properties make this crystal relatively unattractive for high average power OPCPA use. Recently, the linear and nonlinear optical properties of a new class of crystals, the isostructurally related gadolinium and yttrium oxyborates (GdCOB and YCOB), have been characterized[5-7]. These oxyborate crystals have several properties that make them attractive for use in high average and high peak power applications: moderate thermal conductivity (3x KDP), moderate nonlinear coupling (3x KDP or 1x LBO), high fracture strength (10x KDP or 3x LBO), ease of polishing, and compatibility with standard anti-reflection coatings. In addition to these favorable linear, nonlinear, thermo-optic, and mechanical properties, we have demonstrated the aperture scalability of YCOB crystals. Using standard Czochralski crystal growth techniques, we have scaled the growth of YCOB to 7.5 cm diameter x 25 cm length boules. With a single YCOB plate with an aperture of 5.5 x 8.5 cm, we have demonstrated a record 225 W of high-energy second harmonic generation (22.5 J, 10 Hz, 1.8×10^4 shots)[8]. In this Letter we demonstrate for the first time the use of YCOB as an optical parametric chirped-pulse amplifier of 1053 nm pulses. We have utilized YCOB in place of BBO in an OPCPA power amplifier, producing 40 mJ of amplified signal at a 10 Hz repetition rate. The current aperture of YCOB enables the potential scaling of 1 μm OPCPA to over 100 Joules which, along with spectral bandwidths that are equivalent to those of KDP, makes it possible for the construction of a petawatt-class OPCPA system. We also show the results of thermo-optic modeling that indicate the possibility of using YCOB to scale OPCPA to kilowatt average power levels. Finally, given the optical transparency of the crystal, YCOB can generate high average power at a wavelength of 2 μm, when pumped by a 1 μm source.

To test the YCOB gain media, we have utilized an existing OPCPA setup that utilizes BBO as the parametric amplifier crystal[9]. The OPCPA system is designed to produce highly stable and good quality beam profiles at 1053 nm at a repetition rate of 10 Hz. The system is comprised of a femtosecond oscillator, stretcher, compressor, pump laser, and OPCPA preamplifier and amplifier. The seed pulse is generated by a mode-locked Yb:glass oscillator (High Q Laser) that is centered at 1053 nm with a 6-nm FWHM bandwidth. The oscillator produces a 200-fs, 2-nJ pulse, which is stretched to a

800-pJ pulse of 1.2-ns FWHM duration by a diffraction grating pulse stretcher. Pump pulses are generated by a commercial injection-seeded Nd:YAG laser (Continuum Powerlite Plus) that produces 1.5-J, 532-nm pulses with a 5.7-ns FWHM pulse duration at a repetition rate of 10 Hz. The pump beam is split into two beams; a 70-mJ beam to pump the preamplifier (two BBO crystals), while a 570-mJ beam is used to pump the YCOB power amplifier. The output of the preamplifier is resized to 10 mm diameter by a 1:10 expanding telescope. The resulting signal pulse (3 mJ) is injected into two 9 x 12 x 20 mm YCOB crystals arranged in a walk-off compensating scheme[10]. YCOB is a biaxial crystal with point symmetry m (mirror plane m perpendicular to the 'Y' crystallographic axis). The YCOB crystals are cut from a Y-axis, Czochralski-grown boule for type I, 1053 nm + 1075 nm = 532 nm process (standard X-Z principal dielectric plane cut). Both of its input and its output surfaces are antireflection coated for 1053 and 532 nm. The crystals are wedged 2^{o} to prevent parasitic oscillation.

We have obtained 40 mJ of amplified signal energy by using 570 mJ of pump energy and a peak on-axis pump irradiance of 170 MW/cm^2. The conversion efficiency was approximately 14% to both signal and idler, with a pump depletion of 78% of the calculated available pump energy in the 3 ns temporal window (only 18% of the total laser pump pulse energy of 570 mJ is available in the 3 ns temporal window). As shown in Fig. 1, the amplified spectrum exhibits the onset of back conversion as evident by the dip in the center of the signal spectrum. This pronounced dip occurs in the center because the back conversion by sum-frequency generation of signal and idler is strongest there. The intensity autocorrelation of the recompressed amplified signal is shown in Fig. 2. The measured width of the intensity autocorrelation is 1.3 times greater than the calculated transform-limited autocorrelation width based on the measured pulse spectrum. As previously noted[9], this increase in width is due to aberrations in the stretcher-compressor pair. The near-field profile is obtained by imaging the amplified signal onto a CCD camera (Fig. 3). The integrated transverse shape of the amplified signal is a super Gaussian and closely resembles the pump beam profile.

Our YCOB experimental results are comparable to the same OPCPA system using two 10 x 10 x 12 mm BBO crystals for the power amplifier[9]. The higher effective nonlinearity, d_{eff} of BBO (see Table 1) is offset by increasing the total length of the YCOB crystals (40 mm vs. 24 mm for BBO) used for this experiment, while maintaining the same pump pulse irradiance. There was no significant difference in terms of the output spectrum, the recompressed pulse duration, or the near field beam profile. The primary advantage of YCOB over BBO is the availability of the YCOB crystals in large apertures for energy extraction. BBO and LBO are incongruent crystals and are grown from viscous high temperature solutions. The viscous nature of the BBO and LBO melts dramatically increase the crystal growth time, and limits the available clear aperture of either crystal to approximately 2 x 2 cm. Unlike BBO and LBO, YCOB is grown from a low-viscosity, congruent (or nearly congruent) melt. The growth rate of YCOB is 10 times faster than that of BBO or LBO[11]. YCOB is currently grown to boules that allow the production of 8 cm x 20 cm apertures, sizes that traditionally have only been available in KDP crystals[12].

To illustrate the features of YCOB compared to KDP, DKDP, BBO, and LBO for high peak and average power operation, we have written the relevant material parameters for all five crystals in Table 1[13,14]. Maximization of the peak power output of the OPCPA system requires high efficiency energy extraction and a large supported spectral bandwidth from the nonlinear crystals. To directly compare the available bandwidth ($\Delta\lambda$), the length of each crystal is adjusted to produce a fixed gain (G) of 10^3 (a manageable single crystal gain) with a pump irradiance (I_p) of 0.5 GW/cm^2. The crystal length required is given by

$$L = \frac{\ln(4G)}{2C\sqrt{I_p}}, \tag{1}$$

where C is the nonlinear coupling coefficient. As can be seen in Table 1, the required YCOB crystal length is over three times shorter than KDP and DKDP, similar to LBO, and 2 times longer than BBO. As a result, even though YCOB's per unit-length wavelength acceptance is smaller than that of DKDP, the gain-length product allows a YCOB crystal to support the approximate equivalent bandwidth ($\Delta\lambda$) of KDP and DKDP (Table 1). As previously shown, the available bandwidth-aperture of KDP or DKDP is sufficient to support petawatt scale OPCPA laser systems[2]. Maximum output signal energy is a product of the fluence limit, pulsewidth, crystal aperture, and the pump-to-signal conversion efficiency[2]. KDP, DKDP, and YCOB crystals can be obtained in large aperture sizes and have similar damage threshold limits. Extended lifetime operation of YCOB (10^4 shots) at moderate fluence levels (average fluence of 1.2 J/cm^2, peak fluence of 3 J/cm^2) has recently been demonstrated[8].

High average power operation is limited by thermal effects arising from linear and nonlinear optical absorption of the laser pulse and the thermal acceptance of the crystal. One figure of merit that measures the ability of a nonlinear crystal to handle high average power is the "thermally limited power" [14], P_{av}. P_{av} determines the maximum average power that can be tolerated by an edge-cooled frequency converter while still maintaining a high (50%) conversion efficiency,

$$P_{av} \le \frac{16C\kappa\sqrt{I_P}}{\beta_T \alpha} \tag{2}$$

where I_p is the pump irradiance, C is the nonlinear field gain coefficient, κ is the thermal conductivity, β_T is the thermal sensitivity, and α is the linear optical absorption at the pump wavelength. The linear optical absorption measurement of GdCOB/YCOB is based on calorimetry measurements. As shown in Table 1, YCOB has the potential for very high average power operation, as compared to KDP or DKDP (13 kW compared to 0.007 kW and 0.3 kW, respectively). On an equal aperture basis, YCOB also has better average power capabilities compared to BBO or LBO, but the larger available aperture of YCOB compared to BBO allows YCOB to scale to both high average and high peak power systems. YCOB, with its superior thermal properties and low optical absorption, appears well suited for high-average-power, near-infrared OPCPA operation.

In conclusion, we have demonstrated optical parametric chirped-pulse amplification in YCOB for the first time, producing 40-mJ OPCPA output at 1.053 μm. The output energy, spectrum, compressed pulse width, and beam quality are equivalent to the results obtained in the same system utilizing BBO crystals as the final OPA amplifiers. In addition, YCOB is capable of growth to apertures significantly larger than BBO or LBO. The higher nonlinear gain of the YCOB crystal offsets the smaller per-unit-length bandwidth acceptance so that for the equivalent gain comparison, YCOB's bandwidth falls between that of DKDP and KDP. For handling high average power, the large thermal conductivity and vanishing thermal sensitivity[15] enable YCOB to tolerate average power that is over two orders of magnitude greater than that of KDP and 40x greater than DKDP. This is in addition to the fact that YCOB is more mechanically robust and has higher fracture toughness than any of the four crystals. YCOB takes a good optical polish using normal water based polishing techniques. In addition, YCOB has been successfully coated using elevated temperature (300 ^{o}C) high damage threshold optical coatings, whereas KDP and DKDP rely upon solgel-coated surfaces. Finally, unlike KDP or DKDP, the high transparency of YCOB at wavelengths near 2 μm allows the use of this crystal for long-wavelength, high-average-power OPCPA operation – identified as an important research area for high order harmonic generation[16] or shocked cluster experiments[17]. We expect YCOB to play an important role in the average power and peak power scale-up of OPCPA-based laser systems.

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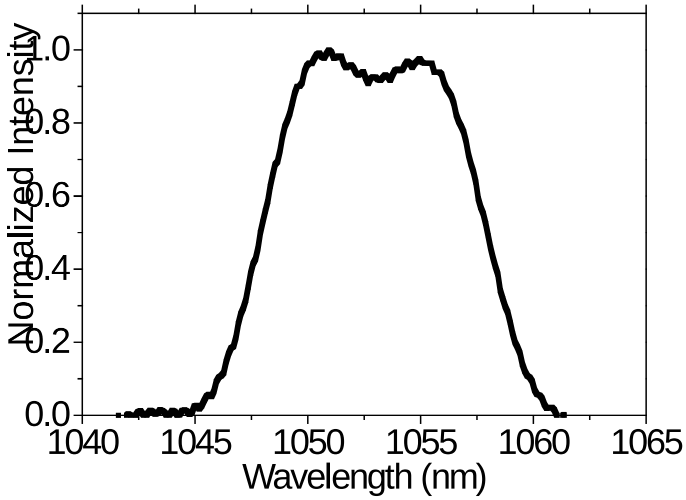

Figure 1. Amplified pulse spectrum produced at the output of the YCOB OPCPA power amplifier. The output energy is 40 mJ. The dip in the center of the spectrum is produced by the onset of backconversion.

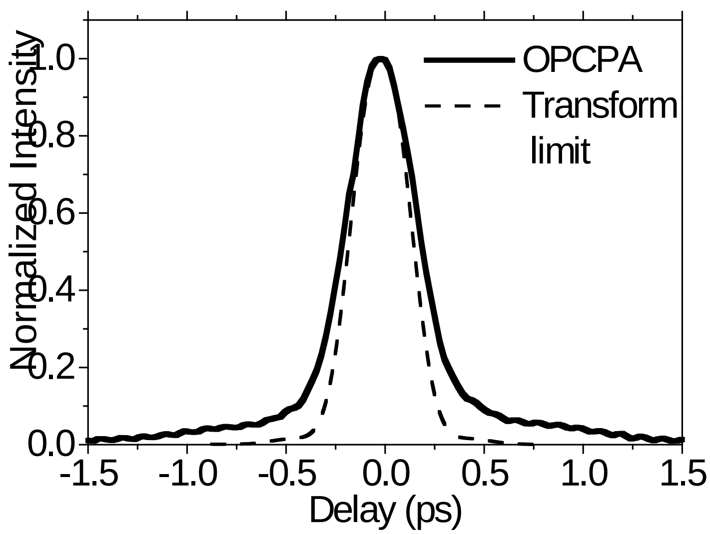

Figure 2. Measured and calculated transform-limited autocorrelation trace based on the measured spectrum (Fig. 1). The measured autocorrelation trace is 1.3 times wider than the transform limited autocorrelation trace due to the aberration limitations in the stretcher-compressor pair.

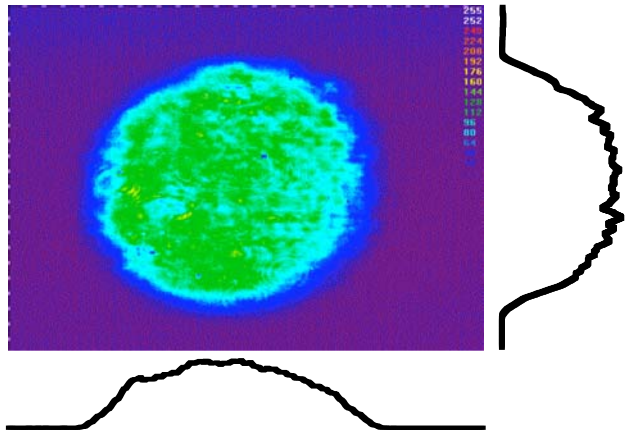

Figure 3. Near field beam profile at the output of the final YCOB OPCPA power amplifier crystal. The output profile matches the pump laser profile.

Table 1. Nonlinear Optical Crystal Parameters (λ_{pump} = 0.532 μm, λ_{sig} = 1.053 μm, I_p = 0.5 GW/cm^2, τ = 3 ns, G = 1000)[13,14]

	KDP	DKDP	LBO	BBO	YCOB
d_{eff} (pm/V)	0.26	0.22	0.83	2.01	0.98
C ($1/\sqrt{W}$)	2.34×10^{-5}	1.96×10^{-5}	6.61×10^{-5}	1.53×10^{-4}	7.22×10^{-5}
β_T (K cm)$^{-1}$	0.37	0.22	0.38	0.11	0.03
α (1/cm @ 1 μm)	0.039	0.0013	0.0015	0.0015	0.0015
κ (W/m/K)	1.3	1.25	3.5	1.4	2.3
Aperture (cm)	40	40	2	2	8 x 20
L (cm)	7.9	9.5	2.8	1.2	2.6
Δλ (nm)	75	45	109	111	52
Energy limit (J)	>1000	>1000	3	3	120
P_{av} (kW)	0.007	0.3	1.5	4.6	13

d_{eff} is the effective nonlinear coupling coefficient, C is the field gain coefficient, β_t is the thermal sensitivity
α is the optical absorption coefficient at 1 μm, κ is the thermal conductivity
Aperture is the currently available aperture limit for the given crystal
L is the crystal length required for a small signal gain of 10^3
Δλ is the full width half maximum of wavelength acceptance for the calculated crystal length
Energy limit is the aperture limited available signal energy for a 3 ns pulsewidth at the above pump irradiance
P_{av} is the side-cooled crystal relative average power limitation as described in the text and Ref. 14.

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